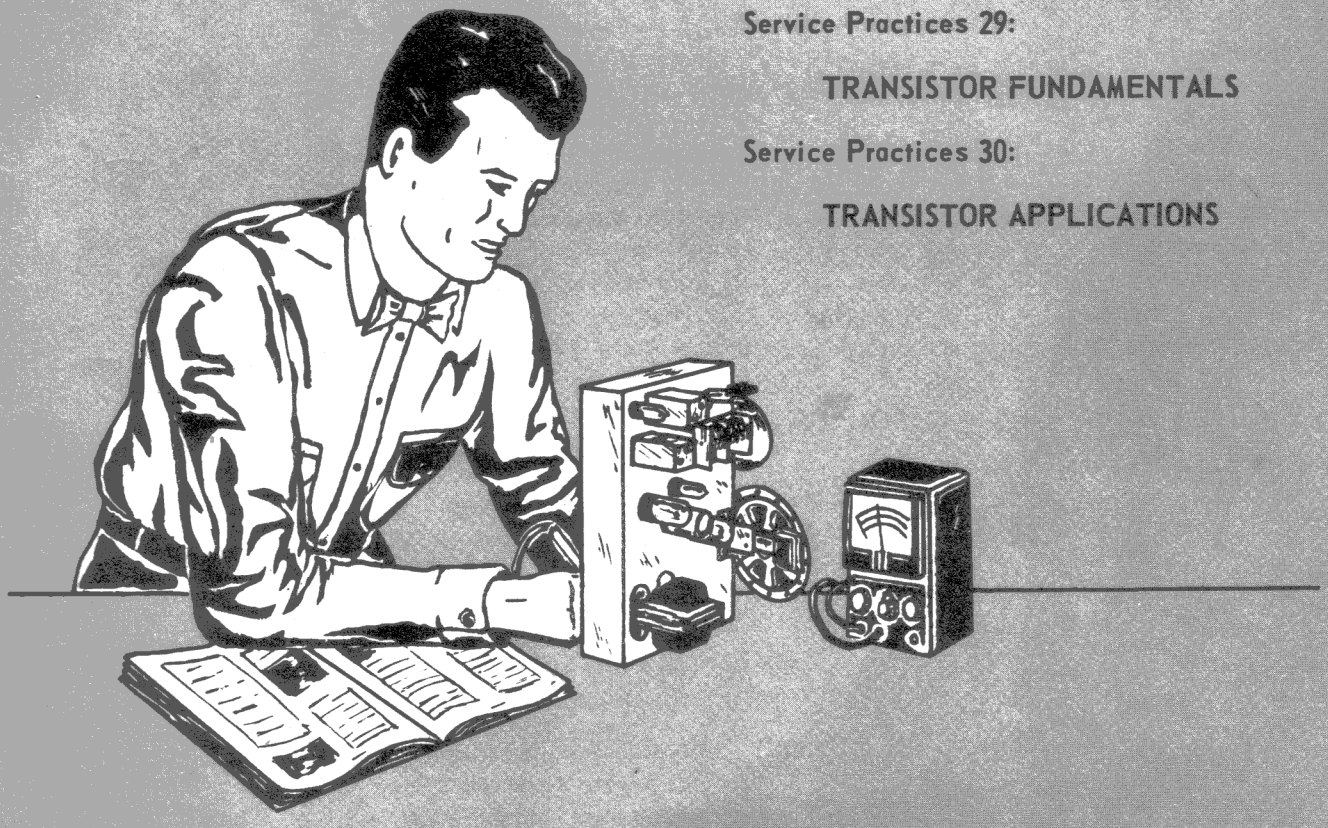
Study Group 15

ELECTRONIC FUNDAMENTALS



Service Practices 29:

TRANSISTOR FUNDAMENTALS

Service Practices 30:

TRANSISTOR APPLICATIONS

RCA INSTITUTES, INC.

A SERVICE OF RADIO CORPORATION OF AMERICA

New York, N. Y.

ELECTRONIC FUNDAMENTALS

SERVICE PRACTICES 29

TRANSISTOR FUNDAMENTALS

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Service Practices 29

INTRODUCTION

The development of many new inventions in the field of electronics is perhaps not startling to us. One new invention after another has led us to believe that this is the normal way of advancement of the Electronics Industry. We have accepted these inventions and proved to ourselves how they operate by applying our knowledge of basic theory. However, transistors are an entirely new concept and require more than just basic electronics to understand their operation. The invention of the transistor in 1948 was not accepted as just a routine development but an achievement destined to make electronics history and leave a lasting impression on the future development of the Electronics Industry.

The transistor has many superiorities when compared to the vacuum tube. Transistors are generally housed in tiny cylinders less than an inch long. They weigh just a fraction of an ounce, have no filaments, consume very little power, have long operating lives, are solid in construction, extremely rugged and free from microphonics. In addition, transistors have no warm up period. They can be made impervious to the weather and in special applications can even operate under water. Their associated circuitry is greatly simplified. They have the ability to oscillate or amplify, serve as an electronic switch, mixer and modulator as well as a detector.

Engineers are designing new products to make use of the advantages offered by transistors. Although there are many types of transistors offered by the leaders of the Electronic Industry, a few of the more popular types are illustrated in Figure 1. It is the intent of this lesson to familiarize you with the theory of operation and characteristics of transistors.

29-1. TRANSISTOR PHYSICS

The study of the transistor can best begin by reviewing the structure of matter. Everything about us is composed of matter. Matter may appear in various states such as liquid or solid. We can best describe matter as that substance of which any physical object is composed.

Take water for example. If we were to repeatedly divide a given quantity of water until we had the smallest amount of water and still not change its *chemical characteristics*, we would have one molecule of water. A *molecule* is, therefore, the smallest amount of a given substance. The single molecule of

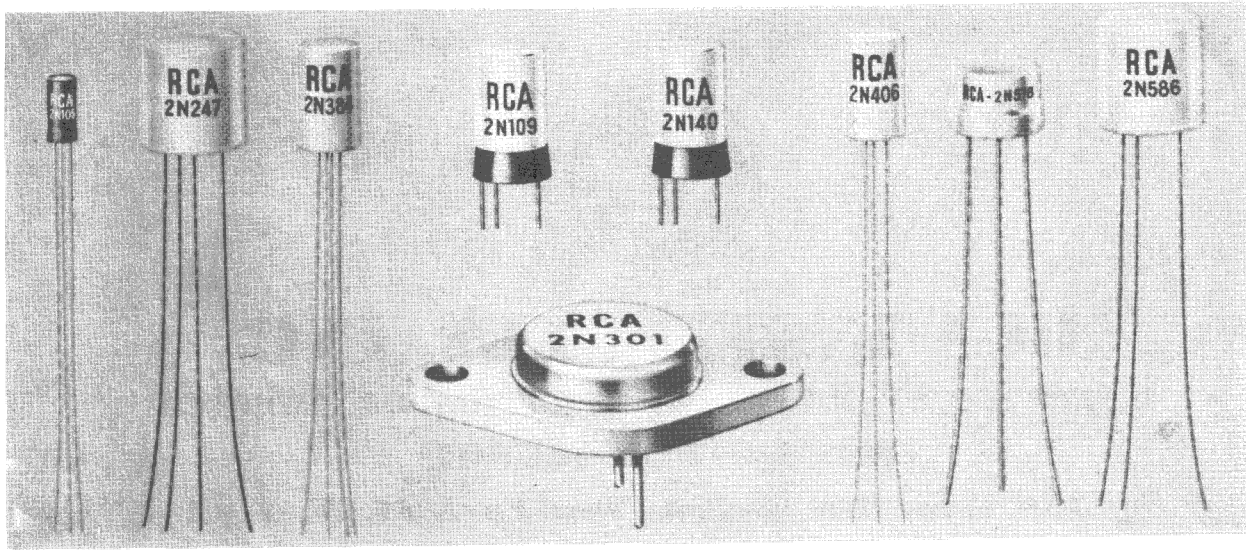

FIGURE 1

water can be further divided into *elements* of oxygen and hydrogen. The smallest subdivision of an element is called an *atom;* therefore, the molecule of water can be split into two atoms of Hydrogen and one atom of Oxygen. In the study of transistors we will be dealing with atoms of germanium, silicon, antimony, arsenic, aluminum and gallium. It will be necessary for us to consider the atomic structure of these atoms.

The Germanium Atom—Germanium is one of the elements most commonly used in the manufacture of transistors. A germanium atom is graphically illustrated in Figure 2 (a). It consists of a *nucleus* in the center and tightly bound *electrons* surrounding it. Upon closer examination it can be seen that the nucleus is composed of 32 *protons* which constitute the principal part of its mass. These protons exhibit a positive charge of electricity.

The nucleus is surrounded by 32 electrons which rotate in fixed orbits. The four electrons in the outer ring are not as tightly bound to the nucleus as those electrons in the inner rings. The electrons in this outer ring are called *valence electrons*. We are mainly concerned with the valence electrons and therefore, we can simplify the diagram of the germanium atom as shown in Figure 2 (b). Here we show a net charge of (+) four in the nucleus which is the total number of protons in the nucleus, minus the tightly bound electrons.

The Silicon Atom—Silicon is another element used in the construction of transistors. In Figure 3 (a) a silicon atom is illustrated. There are 14 protons in its nucleus and 10 tightly bound electrons surrounding it. The valence electrons are shown in the outer ring and as in the germanium atom, there are four.

The simplified diagram of a silicon atom is illustrated in Figure 3 (b) showing only the net charge on the core and the valence electrons. You will notice it looks exactly like the germanium atom. In fact, germanium or silicon can be used equally well in the making of transistors.

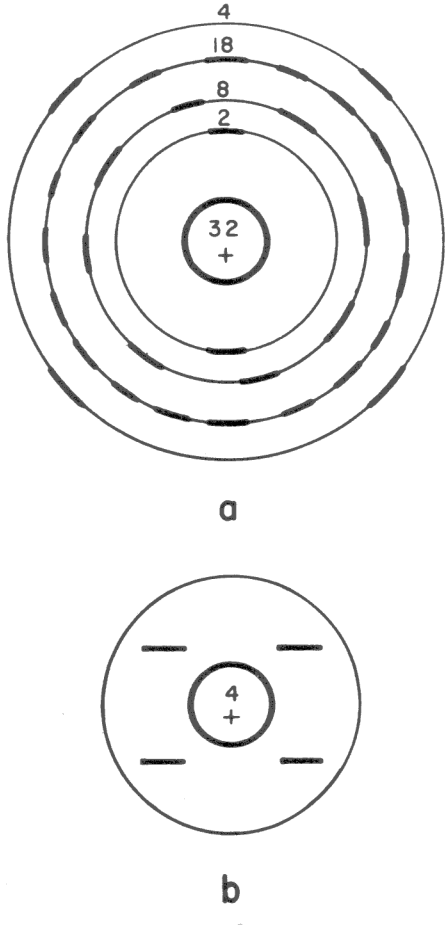

FIGURE 2

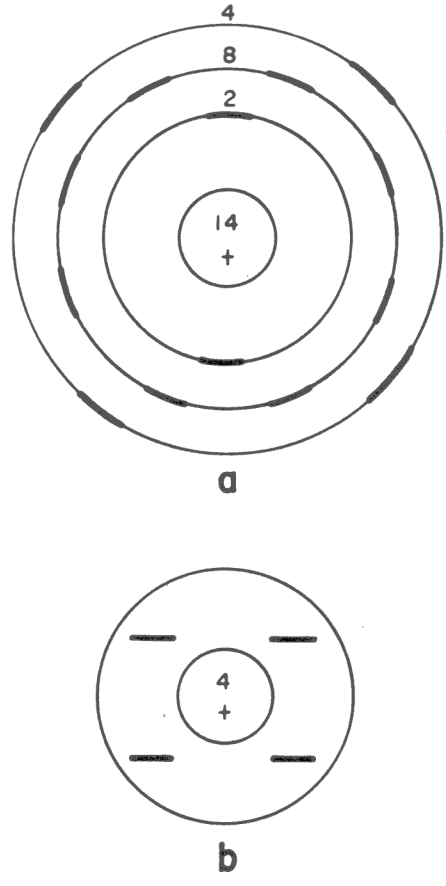

FIGURE 3

We mentioned earlier that antimony and arsenic, in addition to germanium and silicon, can be used in the making of transistors. In Figure 4 (a) are the simplified diagrams of these elements. Note that there are 5 valence electrons for these elements and a net charge of 5 protons. It is important at this time to realize that the number of valence electrons may differ for various elements.

The final two elements with which we shall deal are aluminum and gallium. In Figure 4 (b) we can see that there are 3 valence electrons and a net charge of 3 protons in the nucleus. We shall see shortly how these atoms of various valences are put to use in the making of transistors.

Crystal Structures—Certain substances have the ability to take on a very stable crystalline form. The most popular crystalline substance is the diamond. In this crystalline form valence rings of adjacent atoms interlock with each other. This action of binding the valence rings together is known as the formation of *covalent bonds*. Germanium also has the ability to form covalent bonds. Figure 5 shows the plan by which a pure germanium crystal is formed. Upon examination of the structure you can see that electrons of neighboring atoms interlock with one another.

Keeping in mind the structure of the atom, specifically the valence electrons, we can say whether a particular element is classified as a conductor or insulator by the degree of difficulty with which the electrons can be dislodged from the outer ring. Those elements in which the electrons can not be dislodged easily are called *insulators*. Contrary to this, those elements in which the electrons can be dislodged easily are good conductors. An element which falls somewhere between is a *semi-conductor*. Semi-conductors are the basic materials of which transistors are made.

Semi-Conductors—Two semi-conductors often used for transistors are germanium and silicon. For transistor action, however, it is necessary to control the electrical properties of the semi-conductor material. This control is achieved by the addition of minute quantities of impurities. The impurity can be any of several elements such as antimony, arsenic, aluminum or gallium. The ratio of impurity to germanium need be only 1 part to 10 million. Depending on the type of impurity used, two types of

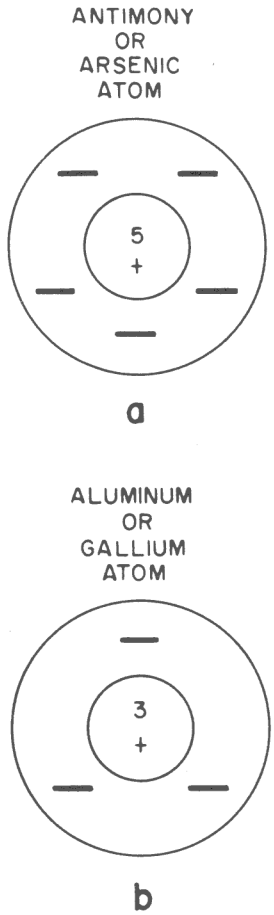

FIGURE 4

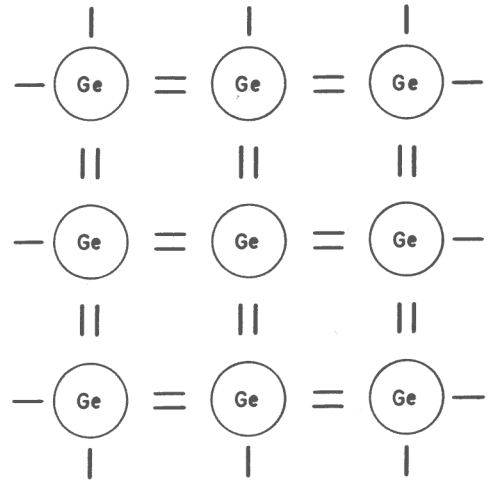

FIGURE 5

semi-conductors will result; namely N-type or P-type.

N-Type Germanium (donors)—Impurities such as arsenic or antimony, having five electrons in their valence ring, may be added to germanium. Four valence electrons of the impurity atoms form covalent bonds with their neighboring germanium atoms.

The fifth electron is free to drift through the crystal structure. The effect of adding arsenic or antimony to the germanium or silicon crystal is illustrated in Figure 6. Impurities that have a valence of five are called *pentavalent-type* impurities or *donors* because they donate electrons to the semi-conductor crystal.

If we were to connect a battery across this type of semi-conductor, conduction takes place. The free electron in the semi-conductor is attracted by the positive potential and enters the positive terminal of the battery as shown in Figure 7. Simultaneously, an electron leaves the negative terminal of the battery and enters the semi-conductor. Thus, a continuous flow of electrons is maintained from the negative to positive terminal as long as the battery potential remains. This type of semi-conductor is called N-type.

P-Type Germanium (acceptors)—A second method of modifying a semi-conductor is by the addition of aluminum or gallium to germanium. In our discussion of elements we noticed that the aluminum and gallium atoms had a valence of three. Remember that the aluminum or gallium atom has one less valence electron than does the germanium or silicon

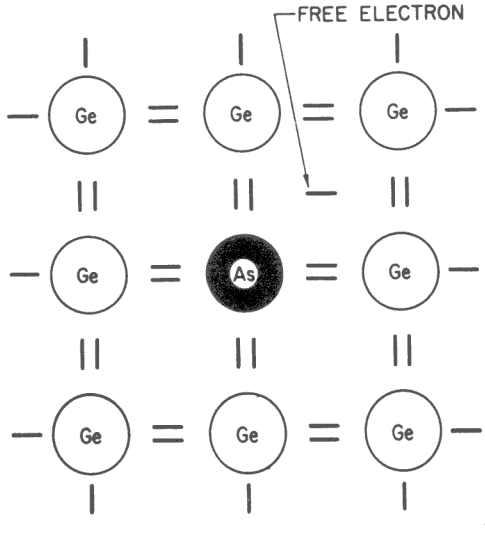

FIGURE 6

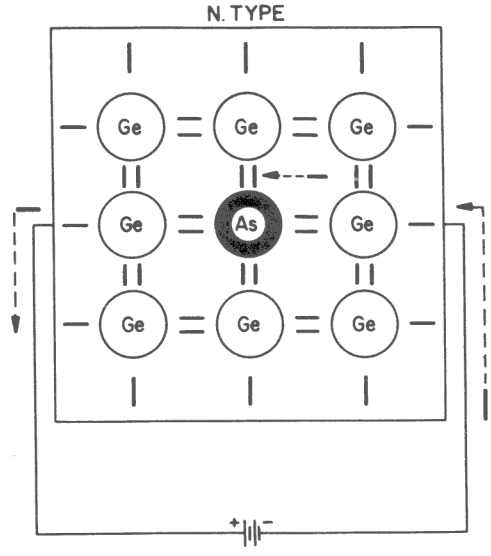

FIGURE 7

atom. Therefore, one covalent bond is incomplete, resulting in a deficiency of an electron or the presence of a "hole." This is illustrated in Figure 8. Impurities that create a hole in germanium or silicon are *trivalent*, meaning a valence of three and are called *acceptors* because they take electrons from the germanium crystal. This type of semi-conductor with acceptor impurities is termed *P-type* germanium.

Let us examine how conduction takes place in a P-type semi-conductor. Figure 9 (a) illustrates a piece of P-type semi-conductor. The hole is shown near the center of the semi-conductor. In reality it may be located any place in the semi-conductor, but for simplicity let us have it exist in the center. A battery is

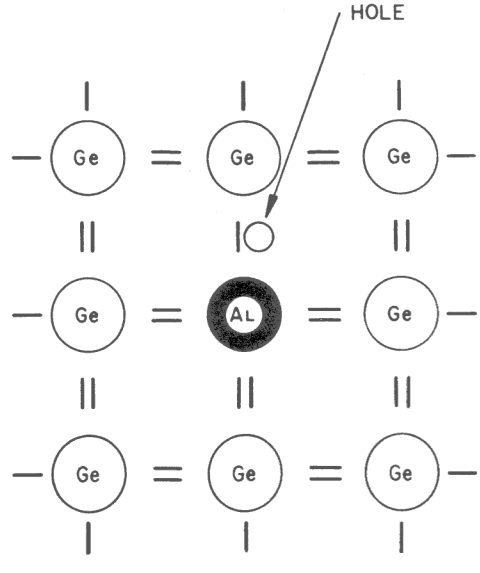

FIGURE 8

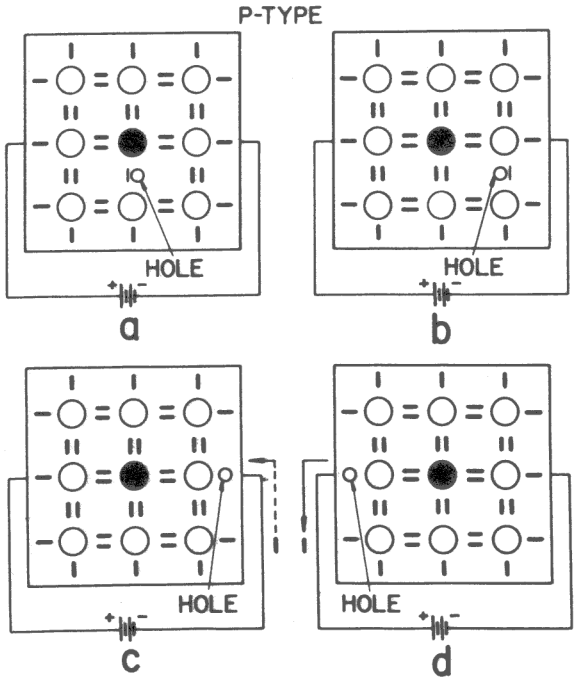

FIGURE 9

also shown. The instant the battery is connected, an electron from an adjacent covalent bond moves from its present position and fills the hole. This action is illustrated in Figure 9 (b). The movement of this valence electron creates a vacancy in the covalent bond it just left. Once again an electron from a covalent bond nearer the negative terminal moves out of the bond and fills the hole. This action is illustrated in Figure 9 (c). The hole is now located on the extreme end of the semi-conductor. In this position there is room for an electron from the supply (negative terminal) to enter the semi-conductor and fill the hole. The instant an electron enters the semi-conductor from the battery an electron from a covalent bond nearest the positive terminal of the battery leaves the semi-conductor and enters the positive terminal of the battery. The removal of this electron from a covalent bond results in the formation of a hole. An electron must leave the semi-conductor in order to maintain the *original characteristic*. That is to have a deficiency of one electron. This action is illustrated in Figure 9 (d). It is possible for conduction to take place within the P-type semi-conductor because by the application of an external supply (battery), valence electrons are made to move into the hole made by the preceding movement of the valence electrons from an adjacent covalent bond. This process is in effect as though the hole was moving toward the negative battery potential. Actually it is the valence electrons that are moving, however, for ease of explanation we will consider hole movement in preference to electron movement in P-type semi-conductors.

Now we have two types of semi-conductors, the N-type and the P-type. The N-type is formed by a donor when arsenic or antimony joins the crystal structure in which electrons are the principal current carriers. The P-type semi-conductor is formed when an acceptor such as aluminum or gallium joins the crystal structure. In this instance holes are the principal current carriers.

Intrinsic Germanium—Absolutely pure germanium or germanium having an equal number of donor and acceptor atoms, has an intrinsic characteristic. Conduction in this type of semi-conductor can only take place if the covalent bonds are broken down by external energy in the form of heat or light. Very pure germanium exhibits some intrinsic conductivity at normal room temperature.

29-2. THE PN JUNCTION

The electrons or holes in semi-conductors of either N or P type are constantly on the move or drifting about in an irregular manner. This intrinsic activity takes place without the presence of an external potential. As we mentioned in discussing the manufacture of N-type semi-conductors, the impurity atom is of the pentavalent type. Keep in mind that the nucleus of the impurity atom is +5 and there are a total of 5 electrons surrounding the impurity atom. This is equal in number to the nucleus and, consequently, the impurity atom exhibits no charge. But this is not always the condition since the excess electron is always on the move.

Now consider the excess electron having moved from its present association with the impurity atom. This time the charge of +5 in the nucleus cannot be equaled by the 4 valence electrons surrounding it. Therefore, the impurity atom takes on a charge of +1. It can be seen then, that as long as the electron is associated with the impurity atom, the atom exhibits no charge and as soon as the electron moves away, the impurity atom takes on a +1 charge.

In the P-type semi-conductor there is a similar activity going on. The introduction of impurity atoms of the trivalent type into

germanium results in a deficiency of an electron or the formation of a hole. Once again this hole is not fixed in the crystal structure but *effectively* moves about. In considering the trivalent impurity atom, we know it has a charge of +3 in its nucleus. But because of its thieving nature it takes an electron from a neighboring valence bond to add to its own 3 valence electrons; as a result there is one more electron than necessary to satisfy the +3 charge on the nucleus. The end result is that the impurity atom takes a −1 charge. As long as the hole is associated with the impurity atom, the atom exhibits no charge and as soon as the hole is filled, the impurity atom takes on a −1 charge.

Although this activity is going on within the semi-conductor without an applied potential, the total mass of the N or P type semiconductors *do not* exhibit a charge. That is, we cannot measure a plus or minus charge on either type.

Keeping this in mind, let us form a piece of germanium with P-type semi-conductor on one end and N-type on the other. This is illustrated in Figure 10 and shows the free holes in the P-region and free electrons in the N-region. The area in the center is designated as the P-N Junction. It might appear at first that some of the free electrons would inadvertently diffuse across the junction, but because of the negative charge exhibited by the fixed impurity atoms in the P-region, they are repelled as illustrated in Figure 11. This is caused by the simple fact that unlike charges attract and like charges repel. The free holes in the P-region remain there for the same reason. That is, the fixed donor atoms in the N-region exhibit a positive charge, thus repelling the holes. The potential which exists at the junction because of the unlike charges on either side is commonly called the *potential gradient* or *potential energy* barrier.

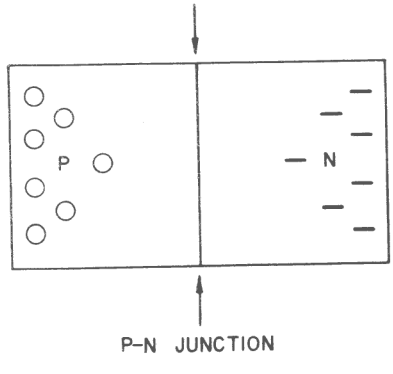

FIGURE 10

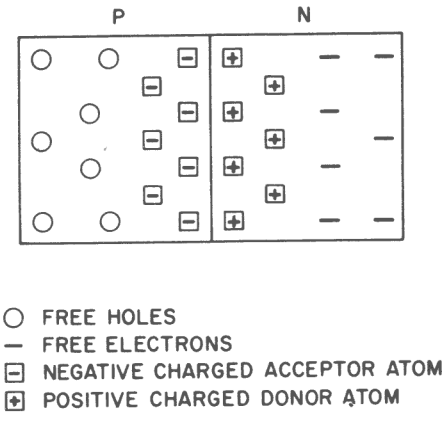

FIGURE 11

Current Flow—Let's connect a battery across a P-N junction as illustrated in Figure 12, and examine the effects. The holes will move to the left toward the negative potential of the battery. Simultaneously, the electrons will move to the right toward the positive terminal of the battery as illustrated in Figure 12. This movement of holes and electrons effectively increases the potential barrier at the junction and there is less chance for electron flow through the P-N junction. We can, therefore, conclude that the resistance to current flow has been increased. The battery connected in this manner is sometimes referred to as *reverse bias*.

Now let us take the same P-N junction and reverse the external battery connections. That is, connect the positive potential to the P-region and the negative potential to the N-region. This is illustrated in Figure 13. This method of connection effectively decreases the potential barrier at the junction and decreases the resistance to current flow.

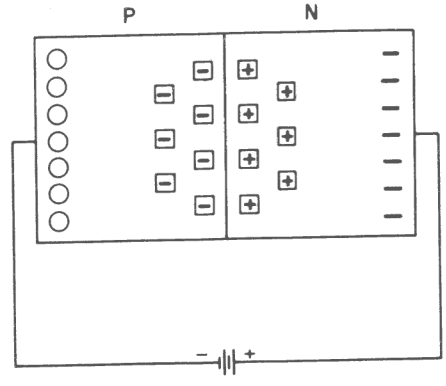

FIGURE 12

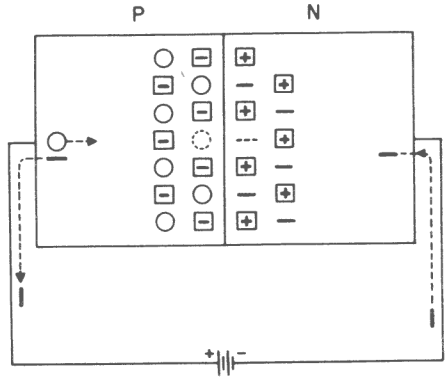

FIGURE 13

The electrons present in the N-region move toward the junction due to the negative potential of the battery. Some of the electrons are forced across the junction and enter the P-region where they combine with existing holes. For each combination, a covalent bond in the P-region nearest the positive terminal of the battery breaks down and the liberated electron enters the positive battery terminal. This action creates a new hole which moves toward the junction. Simultaneously, for each electron that combines with a hole in the P-region, another electron enters the N-region from the negative terminal of the battery and moves toward the junction. The total current flowing through the semi-conductor material is composed of electron flow in the N-region and hole flow in the P-region. The battery connected in this manner is sometimes referred to as *forward bias.*

It is obvious now that the junction formed by the N and P type semi-conductors is capable of rectification. If an A/C signal were applied across the P-N junction, as illustrated in Figure 14, current would flow during the positive half cycle and there would be little or no current flow during the negative half cycle. Therefore, the junction formed by the combination of N and P type semi-conductors is an effective rectifying device and is commonly referred to as a *junction diode.*

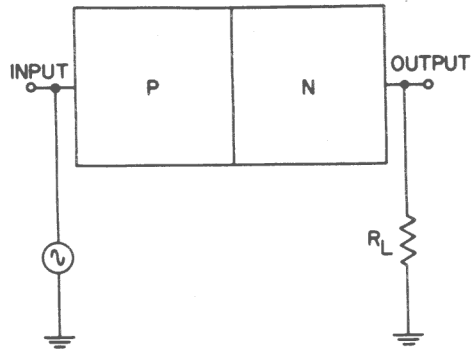

FIGURE 14

29-3. THE PNP AND NPN JUNCTION TRANSISTOR

Although there are many variations of a junction transistor, we can easily understand their operation if we consider them being assembled as a sandwich. The outside layers are relatively thick as compared to the very thin center layer. The important fact being that the semiconductor material is used alternately, such as NPN or PNP. These types are represented by the illustrations in Figure 15. The leads are identified as the emitter, collector and base.

NPN Transistor Action—The transistor illustrated in Figure 16 is of the NPN type. It is impossible for either holes or electrons to overcome the potential barriers formed at the two junctions. Consequently, no current flow is possible without the application of an external voltage source.

Now let us take the NPN transistor and connect the external voltage sources as illustrated in Figure 17. After studying the P-N junction we know that battery A connected as shown, will in effect, reduce the potential barrier between the emitter and base regions. Also, we know that battery B, connected as shown, will in effect increase the potential barrier between the base and collector regions. This battery arrangement will permit electrons to flow from the emitter into the base region. But because the base region is so very thin, most of the electrons will not combine

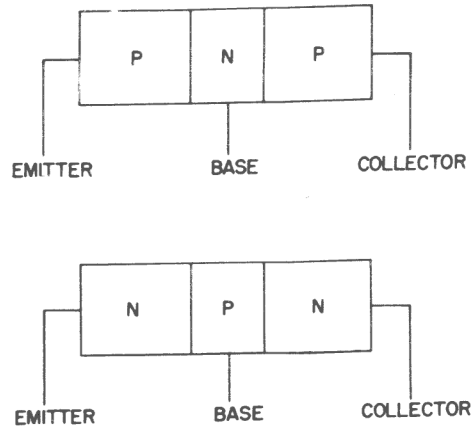

FIGURE 15

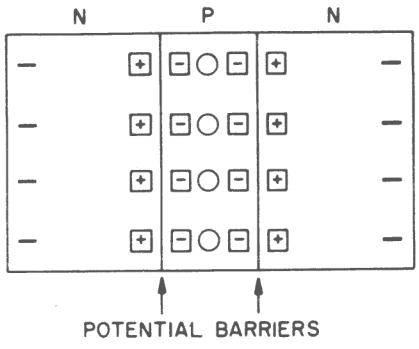

FIGURE 16

with the holes in this region but will pass into the collector region. This electron passage is possible due to the fact that voltage source B, connected across the second P-N junction, is of such polarity that it favors the entrance of electrons from the base to the collector. Once in the collector (N-region), the electrons are attracted to the positive collector electrode, thereby completing their passage through the transistor.

Now let's see what takes place when an A/C signal is applied to the emitter as shown in Figure 18. When the signal swings positive, the potential barrier increases, thereby reducing electron flow through the emitter. When the negative half cycle of the signal is present at the emitter it tends to reduce the potential barrier, increasing electron flow through the emitter. Again because the base region is so very thin most electrons will pass through without combining with the holes and find entrance to the collector.

PNP Transistor Action—A junction transistor of the PNP type is illustrated in Figure 19. It consists of P and N semi-conductors

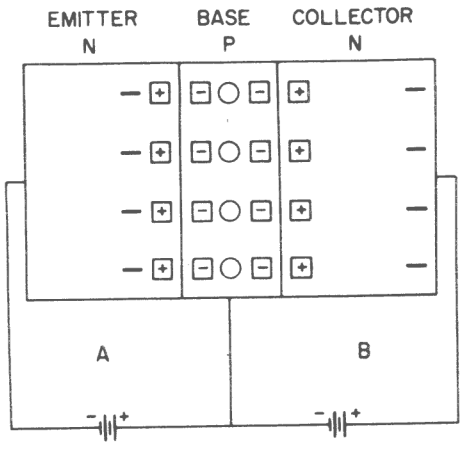

FIGURE 17

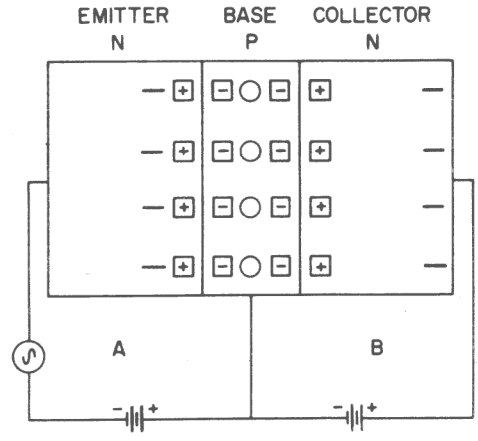

FIGURE 18

used alternately. In order to have conduction in such a transistor, it is necessary that the battery polarity to the emitter and collector be opposite to that used by the NPN transistor. With this connection the holes in the emitter region are repelled by the positive potential of the battery toward the PN junction. Since this reduces the potential barrier existing between the emitter and base, the majority of the holes pass through the relatively thin base area (N-region) into the collector region. A small number of holes are lost by combination with electrons in the base region. As each of the remaining holes enters the collector it is filled by an electron emitted by the negative terminal of the battery.

For each hole lost by combination within the base or collector region, an electron from one of the covalent bonds near the emitter electrode enters the positive terminal of the battery, resulting in the formation of a new hole. The new hole moves toward the junction

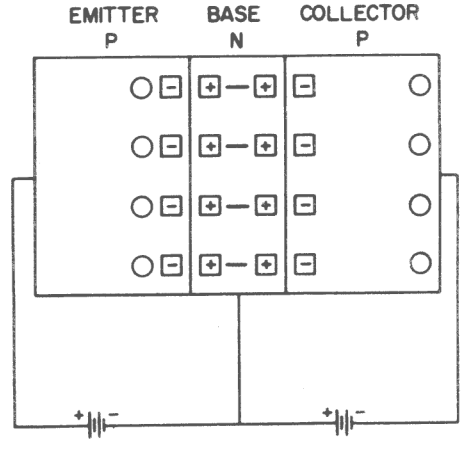

FIGURE 19

area, thus maintaining a continuous flow of holes from emitter to collector.

Amplification in a Junction Transistor— Further investigation of conduction in a junction transistor will show that the emitter current is greater than the collector current. For example, let us consider a case where 1 ma of current flows in the emitter circuit as illustrated in Figure 20. The base current under this condition will be proportional to the number of hole and electron combinations that take place in the base region; also, this base current will be affected by the amount of voltage applied between the base and collector. Under normal operating conditions the voltages are adjusted so that 5% of the total emitter current will flow in the base circuit, the remaining 95% of the emitter current flows in the collector circuit. From this it can be seen that the collector current will be less than unity as compared to the emitter current. The chart in Figure 21 shows the relationship between the collector voltage and current. As indicated by letter A, there will be no flow of current in the collector circuit when the collector voltage is zero. As we increase the collector voltage the collector current will increase linearly until a point of saturation is reached as indicated by the letter B in Figure 21. If we further increase the collector voltage the collector current will remain nearly constant. This response curve is very similar to that of the Ip Ep curve of a pentode vacuum tube. Thus, it can be seen that current flow within the collector region is independent of the collector voltage after the point of current saturation has been reached. Therefore, it is desirable to operate the collector circuit at a voltage indicated by the letter C in Figure 21.

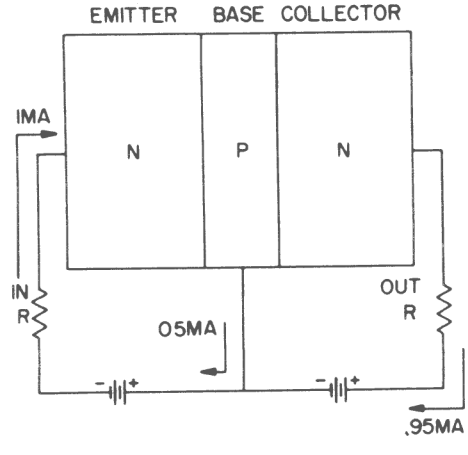

FIGURE 20

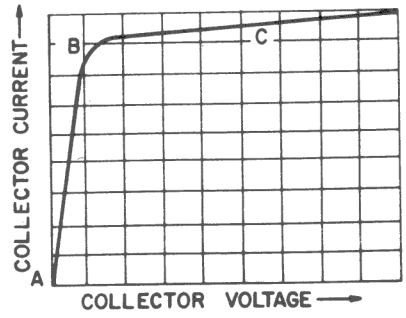

FIGURE 2-21

In order to understand how amplification can take place within a transistor, we must investigate the input and output resistance characteristics of the junction transistor. The battery in Figure 20 is connected between the emitter and base with its polarity such that the potential barrier between the emitter and base is greatly reduced. Current readily flows through this junction, thereby reducing the input resistance to the emitter.

The battery connected between the collector and base is of such polarity that the potential barrier between the base and collector is greatly increased. Thus, the output resistance of the collector circuit is very high. Since we have a low input resistance and a high output resistance, voltage amplification can be effected by a junction transistor. Due to this resistance difference, a small voltage change in the emitter circuit will cause a relatively large voltage change in the collector output circuit. This is due to the fact that a small voltage change at the input will cause a large current change within the emitter. The current change in the collector circuit is directly proportional to the current change in the emitter circuit. Since the output resistance of the collector circuit is relatively high, a change in collector current will produce a relatively large voltage change across this output resistance. This action can be closely related to a pentode vacuum tube circuit, where small grid voltage changes produce relatively large plate voltage changes. From the foregoing it can be seen that if we apply a small A/C signal to the input of the transistor, this signal will be amplified in the collector circuit.

Another factor must be taken into consideration, that is, the peak to peak voltage swing at the input of the transistor must not exceed the battery potential connected between the emitter and base; also the peak to peak voltage swing in the collector circuit must not exceed

the battery potential between the collector and base. If the A/C swing should exceed either of these battery potentials, the signal will be greatly distorted.

Both NPN and PNP type transistors may be used as amplifiers. The only basic difference is that the battery potentials are reversed when comparing these two types of transistors in their circuit applications. The applications of these transistors will be discussed later.

29-4. THE POINT CONTACT TRANSISTOR

The point contact transistor is the result of early experimentation with the germanium crystal. The construction of the point contact transistor is illustrated in Figure 22. It consists of a piece of N-type semi-conductor to which are attached leads known as the emitter, base and collector. An important fact in the construction of the point contact transistor is the method in which the leads are attached to the piece of semi-conductor material. The base lead as illustrated in Figure 23 is a low resistance connection, whereas the emitter and collector leads make contact by the sharp pointed ends of the leads. The emitter and collector leads are high resistance connections.

To understand transistor action in the point contact transistor let us begin by analyzing the emitter portion as illustrated in Figure 24. We learned from a previous section that N-type semi-conductor material has an excess of free electrons, and by the application of a potential across the semi-conductor, electrons will flow through the semi-conductor to complete the circuit. Figure 24 (a) illustrates a negative potential applied to the emitter and a positive potential applied to the base. Under these conditions electron flow will take place.

Let us change the polarity of the supply battery so that the emitter contact is now positive and the base is negative as illustrated

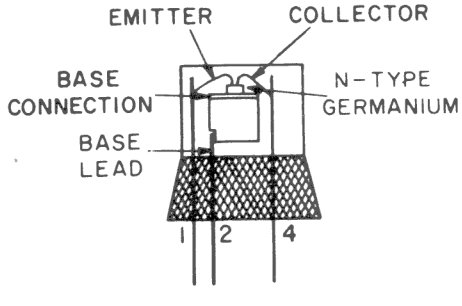

FIGURE 22

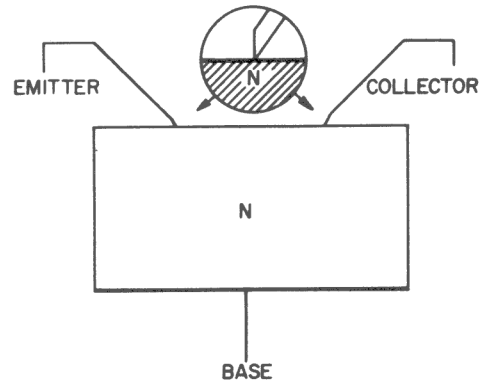

FIGURE 23

in Figure 24 (b). Now the *positive* potential is applied to a small point, rather than being distributed evenly along the entire base area as in Figure 24 (a). The emitter now being positive in polarity results in the attraction of free electrons from the N-type semi-conductor. Thus, electron flow takes place. However, because of the *intense concentration of energy* in the vicinity of the emitter, it not only attracts the free electrons present in the semi-conductor but also withdraws valence electrons from the covalent bond structure in the immediate area. This action of removing valence electrons results in the formation of holes. These holes diffuse toward the base which discharges additional electrons to fill them with the result of *increased electron flow*. It can then be seen that as long as the emitter

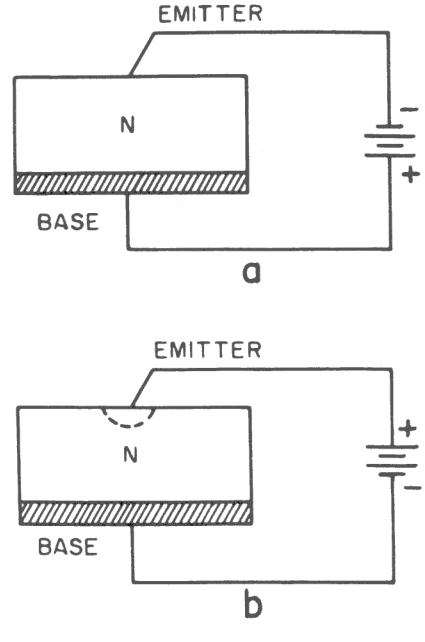

FIGURE 24

is negative in polarity there is relatively little electron flow. However, if the emitter is made positive there is the formation of holes due to the *concentration of energy* present at the point contact, which results in an *increase of electron flow*. Rectification, therefore, is possible.

A simplified diagram of a point contact transistor is illustrated in Figure 25. Consider the emitter and base as constituting one rectifier and the collector and base another rectifier. Battery A, provides a positive potential to the emitter which effectively biases the emitter in the direction that results in the *greatest* electron flow. The battery B provides a negative potential to the collector which biases the collector in the direction of *least* electron flow. Let us consider what takes place in the point contact transistor with the emitter and collector biased in this manner. Figure 26 illustrates the emitter creating holes in its immediate area and in effect creates a space charge consisting of holes. Since the holes were created by virtually pulling an electron from a covalent bond, it is understandable why adjoining electrons want to fill the hole. Since the closest supply of electrons is present at the collector (negative) the holes tend to move toward the negative potential. During their movement toward the collector some holes are filled by electrons, but because of the very close spacing of the emitter and collector a majority of the holes reach the collector. Keep in mind that the collector is biased negatively and consequently, very little electron flow takes place between the collector and base. However, with the presence of the holes in the vicinity of the collector many more electrons can leave the negative terminal of the battery and enter the collector region and fill the holes. Thus, the presence of the holes in the vicinity of the collector causes a marked reduction in the resistance of the collector region which results in an increase in electron flow.

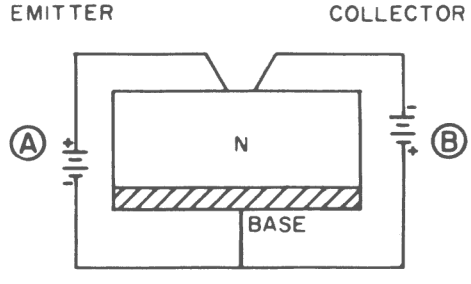

FIGURE 25

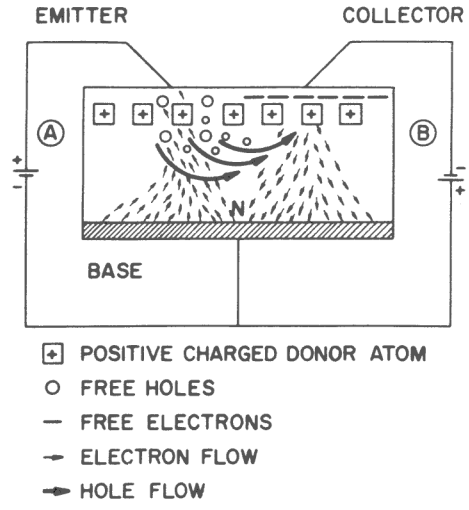

FIGURE 26

From the above theory it can be seen how a signal varying in polarity can be fed to the emitter circuit with the result of corresponding holes being formed in the emitter area. These holes in turn control the resistance of the collector region and result in a corresponding change in electron flow in the collector circuit. Because it takes just a small variation in the electron flow in the emitter circuit to *produce* and *control* a greater electron flow in the collector circuit, amplification takes place.

In average point contact transistors, an increase in emitter electron flow of one milliampere will cause an increase in collector electron flow of 2.5 milliamperes. The current gain factor of 2.5 is typical of point contact transistors. This figure may seem low when compared with the amplification factor of a vacuum tube. However, another factor, the input and the output resistance of the transistor plays an important part. The input resistance is approximately 300 ohms, while the output resistance is approximately 20,000 ohms. It can be seen that there is another gain characteristic, namely the resistance gain. The transistor voltage gain equals the current gain times the resistance gain. Therefore, the voltage gain obtainable is comparable to a Hi-Mu vacuum tube.

29-5. TRANSISTOR CHARACTERISTICS

Symbol and Lead Identification—The symbols used for transistors are illustrated in Figure 27. The symbol in Figure 27 (a) is of the conventional type presently in widespread use. The heavy horizontal line represents the base and the two angular lines repre-

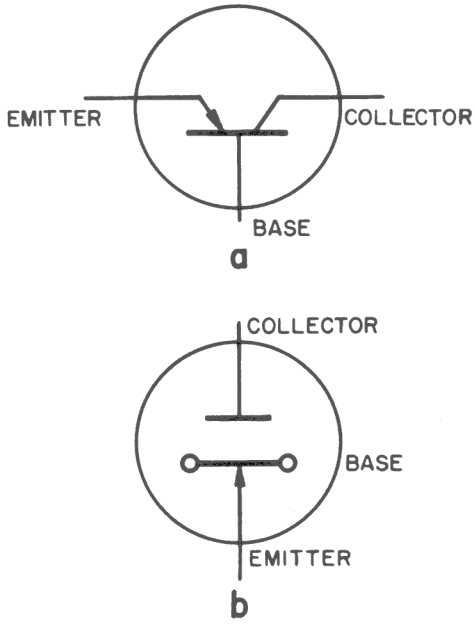

FIGURE 27

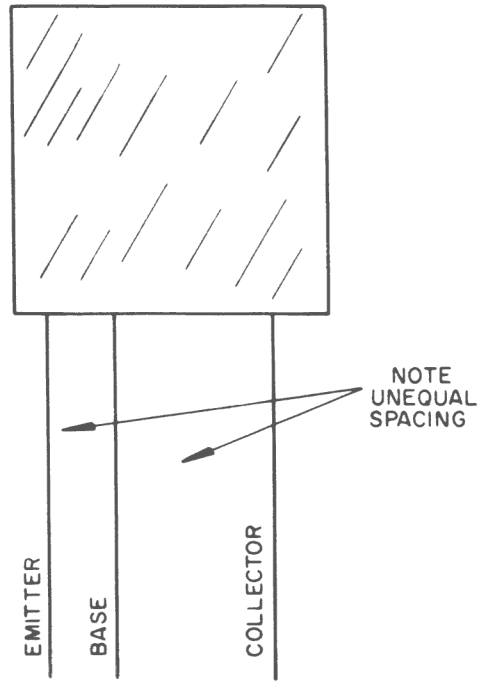

FIGURE 28

sent the emitter and collector. The arrow head, drawn on the emitter indicates the direction of *current* flow. This provides an aid in identifying the type of transistor. In the case of a junction transistor of the PNP type, the arrow is drawn pointing toward the base. An NPN type is drawn with the arrow in the opposite direction.

Another symbol used to represent a transistor is illustrated in Figure 27 (b). This is perhaps more representative of the actual transistor construction and relationship of the elements in comparison to the vacuum tube symbol. The arrow also shows the direction of current flow in the emitter.

The leads on an actual transistor are readily identified by the position and spacing of the leads. A "standard" transistor is illustrated in Figure 28. The base lead is the center lead. The emitter and collector leads are on either side of the base lead. The collector lead can be identified by the larger space existing between it and the base lead.

Methods of Operation—In general, the transistor can be compared to a vacuum tube. The illustration in Figure 29 shows the similarities. The base is similar to the grid of the vacuum tube in that they both serve to control electron flow through the unit. The emitter and cathode supply the source of electron flow. The collector of the transistor and the plate of the vacuum tube are similar in that they both are normally part of the output circuit.

The transistor's input and output impedance can be varied by the method in which it is connected in a circuit. Figure 30 illustrates the various methods of operating a transistor. A comparable connection of a vacuum tube is shown below each method. In each instance one electrode is common to both the input and output circuits. The common base type is illustrated in Figure 30 (a). This type of operation is similar to a vacuum tube used as a grounded grid amplifier. The advantage of using a transistor in this manner is that it has a low input impedance and a high output impedance.

The common collector type is illustrated in Figure 30 (b). This is similar to a vacuum tube used as a cathode follower. With a common collector, the impedance characteristics

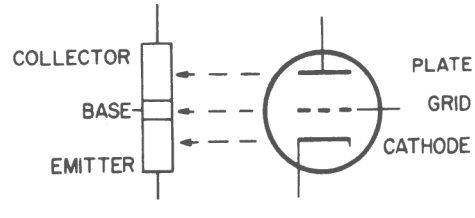

FIGURE 29

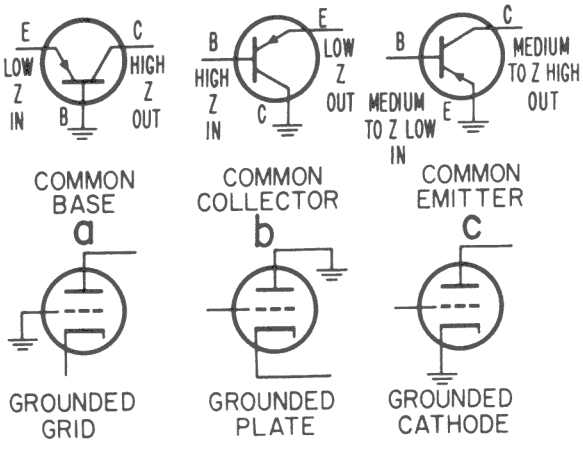

FIGURE 30

of the transistor are such that the input now possesses a high impedance and the output a low impedance.

The final method of operation is the common emitter type and is illustrated in Figure 30 (c). This is similar to a grounded cathode vacuum tube circuit. The input impedance is medium to low and the output impedance is medium to high. The grounded emitter is generally employed in conventional circuit applications. For use in special circuits the correct impedance match can be made by choosing the proper method of connection. Thus, almost any impedance ratio can be inserted to satisfy the circuit requirements.

Electrical Characteristics — The manufacturer of transistors generally supplies the mechanical and electrical characteristics in the form of a specification sheet. Let us examine the specifications pertaining to an RCA type 2N109 junction transistor.

The manufacturer tabulates the specifications of transistor units in the following categories; general data, maximum rating, typical operating characteristics and characteristic curves.

General data includes the following:

Electrical:

Maximum DC Collector Current for dc collector-to-base voltage of —25 volts with emitter open, and at ambient temperature of 25°C	—10 μ amp
Maximum DC Emitter Current for dc emitter-to-base voltage of —25 volts with collector open, and at ambient temperature of 25°C	—10 μ amp

Mechanical:

Mounting Position	any
Maximum Overall Length	0.697″
Maximum Seated Length	0.495″
Maximum Diameter	0.260″
Case	Metal, Insulated
Envelope Seals	Hermetic
Base	Small-Round Linotetrar 3-Pin (JETEC No. E3-25)

Maximum ratings are those values of voltage, current and temperatures that must not be exceeded when operating the units. The values given are important not only to the electronic engineer but also to the service technician. The maximum ratings for the RCA type 2N109 transistor are as follows:

Maximum Ratings:

Peak Collector-to-Base Voltage	—25 max. volts
DC Collector-to-Base Voltage (for inductive load)	—12 max. volts
Peak Collector Current	—70 max. ma
Average Collector Current	—35 max. ma
Peak Emitter Current	70 max. ma
Average Emitter Current	35 max. ma
Collector Dissipation	50 max. mw
Ambient Temperature (during operation)	50 max. °C
Storage-Temperature Range	—55 to +85°C

Characteristics:

DC Collector-to-Emitter Voltage	—1 volt
DC Collector Current	—50 ma
Large-Signal DC Current Transfer Ratio	70

The voltages are generally given with respect to the base and the values indicated in volts. Current is given in milliamperes or microamperes and the power dissipation values are given in watts or milliwatts.

Typical Operating Characteristics are also given to serve as a guide to the engineer who may be designing equipment or the technician servicing the equipment. The following information is for the RCA type 2N109 transistor. This transistor is used primarily for Class B operation, and the operating characteristics are as follows:

Typical Push-Pull Operation:

DC Collector-to-Emitter Supply Voltage	—4.5	—9	volts

DC Base-to-Emitter Voltage	−0.15	−0.15	volt
Peak Collector Current (per transistor)	−35	−40	ma
Zero-Signal DC Collector Current (per transistor)	−2	−2	ma
Max.-Signal DC Collector Current (per transistor)	−11.5	−13	ma
Signal-Source Impedance (base to base)	1500	1500	ohms
Load Impedance (collector to collector)	400	800	ohms
Signal Frequency	1	1	kc
Circuit Efficiency	60	69	%
Power Gain	30	33	db
Total Harmonic Distortion	7	7	%
Max.-Signal Power Output	75	160	mw

Characteristic curves are also included as part of the specification sheet. These curves are similar to the curves furnished for vacuum tubes and serve a similar purpose. A typical curve is illustrated in Figure 31.

Temperature Effects — All semi-conductors are subject to temperature limitations. In well designed germanium transistors the maximum rated temperature is approximately 185°F (85°C). In most applications temperatures seldom exceed 150°F, therefore, there is a sufficient margin of safety. In special applications, as in military equipment, it is desirable to operate the equipment over a wide range of temperatures. It is here that the silicon transistor plays an important role. Silicon transistors are available that operate with temperatures of 350°F with no destructive effects.

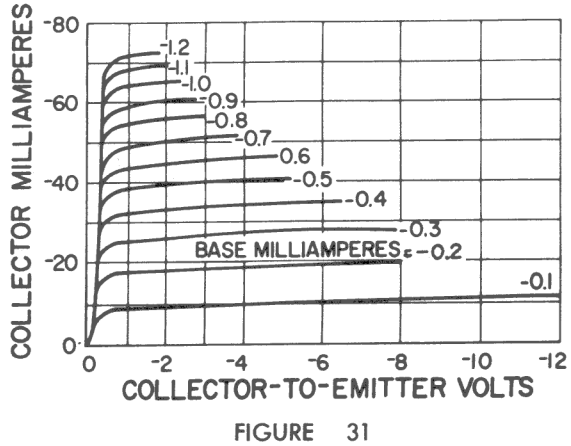

FIGURE 31

Frequency Cut-Off—The upper frequency limit of transistors is determined by the time required (transit time) for the electrons to pass from the emitter to the collector. By making the base of the transistor thinner the element of time will be reduced and consequently, a higher frequency cut-off obtained. It is along these lines that research engineers are constantly working.

In order to obtain transistor performance which is equal to the vacuum tube, the maximum operating frequency should be about 20% of the frequency cut-off. Therefore, in applying this rule, it appears that the minimum cut-off frequency for a portable or home radio receiver with an IF of 455 KC is at least 2-2.5 mc. For mixer operation of the broadcast band a cut-off of 8 mc is required. A television VHF RF transistor amplifier operating at 200 mc would need a 1000 mc cut-off frequency. There are commercial transistors available that satisfy the requirements for radio and VHF television receivers.

There are other types of transistors which we will discuss in the next section, some of which are capable of operating at UHF television frequencies.

Reliability —The early transistors were incased in plastic. This afforded protection to the unit. Incased transistors used in hearing aids provided good service for over three years. There are several disadvantages, however, in this method of protection: the plastic units did not stand up well at high temperatures, nor could they survive under extreme moisture conditions. As a result, extensive effort was directed toward the development of hermetically sealed, metal cased units. This method presented new problems; at first it was noticed that some units were subject to abrupt failure in varying percentages due to air leaks. Second, some of the units that were truly sealed, died slowly as the result of the gradual release of internal contaminants. Today, due to experience gained in the past few years, these problems are practically eliminated. To insure the best possible service, accelerated life tests at high temperatures are used to predict long and useful transistor life.

29-6. TYPES OF TRANSISTORS

In the past few years the development of transistors has led to many variations in their design and construction. Let us briefly consider the features of various types.

The Alloy-Junction Transistor—The alloy method of constructing a junction transistor is illustrated in Figure 32. The base of the transistor is a wafer of N-type semi-conductor. The collector and emitter regions are formed by placing pellets of a trivalent impurity on opposite sides of the N-type wafer and applying heat so that the impurity alloys into the N-type semi-conductor. This alloying process forms regions of semi-conductor material of the P-type which constitute the emitter and collector. Complete control of this process provides separation between the emitter and collector of about .0005 inch which permits a short electron transit time from emitter to collector. In addition, the resistance between the base connection and either the emitter or collector is low because of the relatively thick N-type wafer used. Finally, the various capacitive effects of the emitter and collector are kept to a minimum because of the very small areas of the P-type regions. Transistors made by this process exhibit 12 db of gain at 10 mc and a frequency cut-off of approximately 75 mc. This method of construction is feasible for both PNP and NPN types of transistors.

The Drift Transistor—The high frequency performance of transistors is limited by three basic factors. These are the time it takes for a hole or electron to travel through the base region, the input resistance, and the collector capacitance. The drift transistor structure minimizes these factors and makes possible devices capable of operating at very high frequencies.

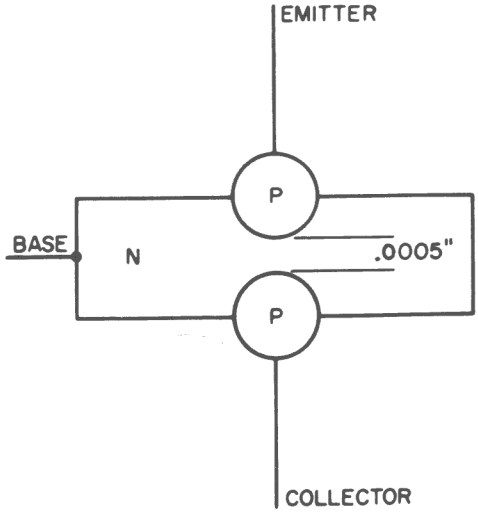

FIGURE 32

The method used in a drift transistor to reduce the transit time for a given base dimension is to establish a field within the base region that will directly aid the passage of holes or electrons. This field is established by varying the conductivity of the base region so that the conductivity is high near the emitter and low near the collector. The drift transistor illustrated in Figure 33 shows by means of vertical lines the regions of high and low conductivity. The conductivity of the base material is controlled by the distribution of impurity atoms during manufacture. The highest concentration of impurity atoms is near the emitter and the lowest concentration near the collector. In such a non-uniform conductivity distribution, the electron density (in N-type base material, for example) is greatest in the high conductivity region. The electrons tend to drift out of the region of high concentration. As a result, an electric field is set up due to the positive charge on the atoms from which the electrons left.

The positive charge of the drift field tends to keep the remaining electrons near the emitter side of the base. The holes injected by the emitter are accelerated by the drift field toward the collector because of their opposite charge. The drift field reduces the transit time to one-fourth of that of a conventional alloy-junction transistor of the same base dimension. In addition to an improvement in transit time, the high frequency performance is improved because the high conductivity of the base region near the emitter reduces the input resistance. Also, the low conductivity near the collector region results in a low collector capacitance. Thus, the upper frequency limit of the drift transistor is much higher than that of a conventional PNP transistor. These devices are capable of oscillating at frequencies up to 300 mc and are usable as amplifiers at VHF television frequencies.

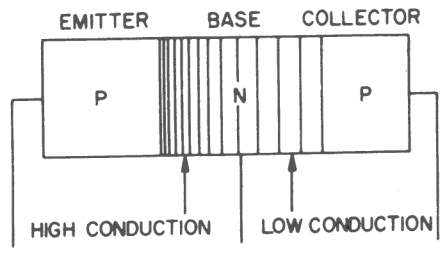

FIGURE 33

The Tetrode Transistor—The tetrode transistor derives its name from an additional lead attached to the base region. Thus, there are four leads extending from a tetrode transistor. Figure 34 illustrates the tetrode transistor. The additional lead is attached to the base region at a position which is on the side opposite to that of the original base connection. The bias voltages necessary to operate this type of transistor are similar to those required by a conventional NPN type of transistor. The emitter is biased in the direction of greatest electron flow, and the collector is biased in the direction of least electron flow. The fourth lead is biased at a negative potential which is considerably greater than the normal emitter to base potential. The presence of this negative potential restricts the electrons flowing through the base region so they flow through a relatively narrow area of the base region. The flow of electrons is illustrated in Figure 34.

The advantage of the use of the tetrode structure is an improvement in high-frequency operation. This improvement is obtained from the reduction of emitter and collector capacitance due to the reduced effective area of each region adjacent to the base region, as well as a reduction in base resistance due to the shorter path travelled by the base current. A limitation of the tetrode is its power handling capabilities. In forcing the electrons to flow in a narrow channel in the base region there is a reduction in the collector current capability. Fortunately, the power requirements for the high frequency stages in many commercial applications are very low. Therefore, this limitation is not of prime importance. A transistor of this type is suitable for use in IF stages of television receivers.

Power Transistors—Along with high current and voltage capabilities, the effective dissipation of heat is one of the prime requirements for a power transistor. In some circuit configurations an increase in transistor temperature will cause a bias point shift resulting in an increase in dissipation and hence increase the device temperature even more. This cycle can continue until "thermal runaway" occurs, damaging the transistor. In properly designed circuits this effect can be minimized. However, unless the heat generated can be removed efficiently, the transistor junction temperature will rise to an undesirably high level and, in time, the performance of the transistor will be significantly degraded.

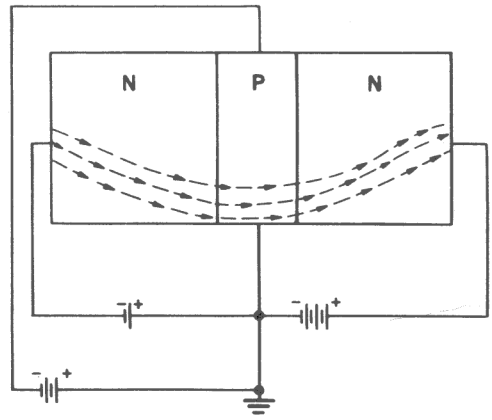

FIGURE 34

Most of the heat dissipated in a transistor is generated at the collector junction. In order to simplify removal of this heat the collector dot is generally fastened directly to the case of the unit (see Figure 35). Provision is then made for the case to be directly connected to a chassis or other heat dissipating surface. Power transistors of the structure described are now available and are capable of dissipating up to 25 watts in practical applications.

Surface Barrier Transistors—The structure of the surface barrier transistor is similar to that of an alloy transistor. One major difference in structure is that instead of alloying dots deeply into the base material to obtain a narrow base width, two wells are electrochemically etched into the base material until they are separated by only a few tenths of a mil. Indium is then plated on both sides and emitter and collector contacts made (see Figure 36). Such a unit has frequency cut-off in the order of 40 mc.

Recently, the micro-etching techniques used to make surface barrier transistors have been applied to "drift" transistor structures. The units produced by this process have been termed micro-alloy diffused transistors. Such a unit has a frequency cut-off greater than 250 mc and finds wide application in high speed computer circuits.

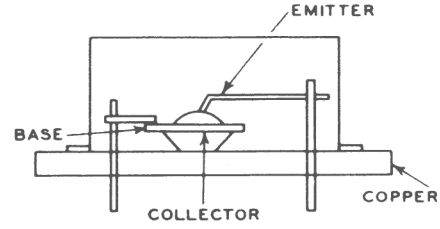

FIGURE 35

Photosensitive Transistors—Photosensitive transistors can be divided into three groups according to their construction; they are, the point contact, the PN junction and the phototransistor. These various types of photosensitive transistors are used to control photoelectric equipment such as flame detectors, automatic door openers, automobile light dimmers, burglar alarms and counters. The mechanical features of these photosensitive transistors are similar to the conventional transistor in that they are lightweight, rugged, etc.

A photosensitive transistor of the *point contact* type is illustrated in Figure 37. The heart of the device is a wafer of germanium. One side has a spherical "dimple" ground into it. This is done to reduce the thickness at the center to about .003 inch. The wafer is force-fitted into one end of a metal cartridge and a pointed phosphor-bronze wire is brought into contact with the wafer at its center. This wire is called the collector. The other end of the wire fastens to a metal pin contact embedded in an insulating plug which is positioned at the opposite end of the case. The second electrical contact to this phototransistor is the case itself.

The wafer is made of N-type semi-conductor and is biased in the direction of *least* current flow. When light is directed on the germanium wafer a number of covalent bonds are broken, thus producing an equal number of holes and electrons. Under the influence of the applied electric field, the electrons travel to the positive terminal of the battery and the holes go to the negative battery terminal. It is because of the additional carriers of current made available by the action of light on the N-type germanium, that there is an increase in current flow through the circuit.

To insure that maximum current response is obtained when the light rays fall in the

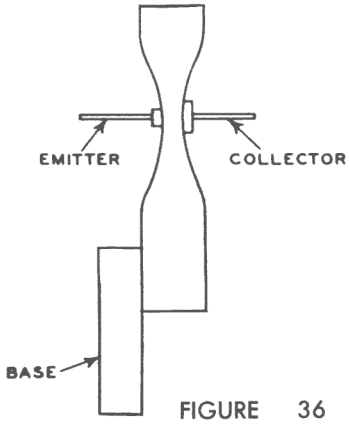

FIGURE 36

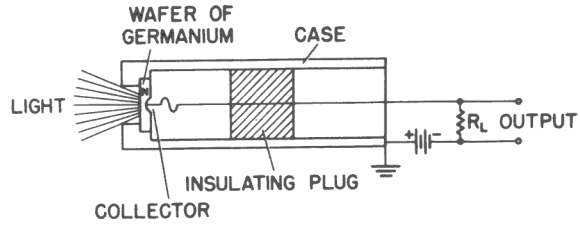

FIGURE 37

vicinity of the point contact a small glass lens is used to focus the light rays into a narrow beam which is restricted to the desired area of the N-type wafer.

A photosensitive transistor of the PN junction assembly may also be devised with comparable results. A junction phototransistor is illustrated in Figure 38. The response will be greatest when the light is directed at the junction.

Another form of a photosensitive transistor is the phototransistor. This unit employs an NPN type of construction as illustrated in Figure 39. Only the central base section is

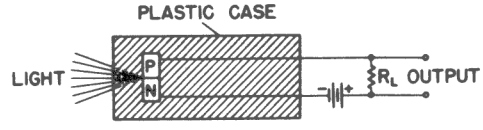

FIGURE 38

made photosensitive. The bias battery is adjusted so that very little current flows through the transistor, however, when light is focused on the base section, holes are formed in sufficient quantity to produce an increase in current to operate a relay directly. A practical application of this type of phototransistor is in the automatic auto headlight dimmer.

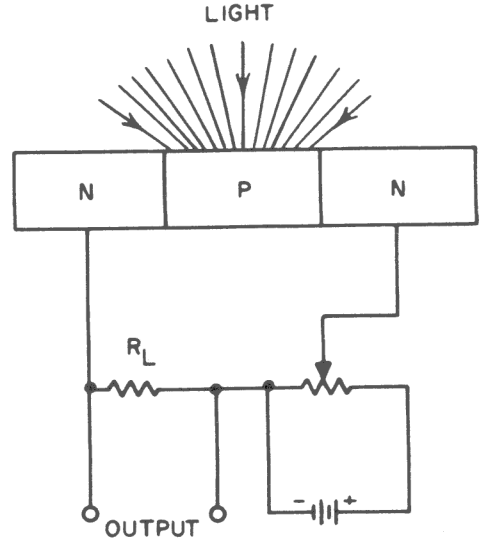

FIGURE 39